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Effects of Acid Precipitation on Coniferous Forest

by

G. Abrahamsen, K. Bjor, R. Horntvedt and B. Tveite.

Contents

Abstract

Increased foliar leaching of nutrients with increased rain acidity was indicated by throughfall sampling and was also experimentally confirmed.

Irrigation of field plots and lysimeters with acidified water increased the leaching of metal cations and reduced the base saturation in the top soil. Soil biological processes were little influenced by application of water with pH from 6 to 2.

Spruce seed germination and seedling establishment were negatively influenced by acidification.

Regional surveys of diameter growth in spruce and pine are as yet inconclusive with regard to acidification effects. Some acidification experiments have shown no effect, and others an increase in height growth with increasing acidification.

1. Introduction

The increasing emission of air pollutants in general, and in particular those forming acid components, represents a possible threat to natural ecosystems *(Odén* 1968, *Royal Ministry for Foreign Affairs* & *Royal Ministry of Agriculture* 1971, *Likens et al.* 1972).

Freshwater ecosystems are especially sensitive to the acidification (*Jensen* & *Snekvik* 1972, *Leivestad et al.* 1976), but serious concern has also been expressed with regard to the effect on terrestrial ecosystems (*Dahl* & *Skre* 1971, *Malmer* 1973).

Forests occupy large areas, they have a significant ecological value as a habitat of a variety of organisms, they influence other ecosystems like watercourses and they have high economic value. For these reasons predictions of reduced forest production (*Dahl* & *Skre* 1971) have been received with great concern.

However, predictions of this kind must be considered tenative. Even though some compounds in air and precipitation are harmful, others are likely to be beneficial to forest production. Uncertainties also arise because negative effects such as increased leaching from soil or reduced bacterial activity, may be counteracted by other effects such as increased weathering or fungal activity. The effects of acid precipitation are therefore varied and complex.

Consequently, studies of the effects of acid precipitation should include the main components of the ecosystem in question. The studies described in the present paper aim at investigating the effects on trees and some selected main factors which influence tree growth.

Preliminary results of these studies have been previously reported (*Abrahamsen et al.* 1975).

2. Description of field studies

Field studies were given priority in the first phase of The SNSF-project. Experiments with field plots were established at Nordmoen, at Sønsterud and at Åmli – all areas located in southern Norway (Fig. 1). The experiments at Nordmoen and at Åmli have been described by *Abrahamsen et al.* (1976a).

The main objective of the experiments is to study the effect of simulated acid rain on tree growth. The experiments at Nordmoen, which include lysimeters, and at Åmli also serve for studies on chemical and biological processes in soil. Studies on foliar leaching and on ground cover vegetation were carried out in some of these experiments.

Studies on tree growth were also based on comparisons of past diameter growth between regions assumed to differ in exposure to acid deposition (Fig. 1), or between sites receiving approximately the same acid input but supposedly differing in sensitivity owing to soil properties (*Tveite* & *Skrøppa* 1976).

The main studies on foliar leaching and dry deposition were carried out in Birkenes and in Målselv (Fig. 1) (*Bjor et al.* 1974, *Horntvedt* & *Joranger* 1974). Birkenes is located in an area heavily exposed to deposition of long-range transported air pollutants. Målselv serves as a control area.

The field plot and lysimeter experiments are, with the exception of the experiment in the forest nursery (Sønsterud), carried out in relatively oligotrophic and acid podzol soils (*Abrahamsen et al.* 1976a). According to *Wiklander* (1973/74) this soil has a high resistance to pH-change and the net effect of acid precipitation is assumed to be small. However, this particular soil covers about 80% of the productive forest area in Norway (*Låg* 1970), and any adverse effects of acid precipitation would therefore be of concern.

The field experiment in Åmli and one of the experiments at Nordmoen are carried out on podzol soils. Another experiment at Nordmoen is on an intermediate soil type between podzol and brown earth (*Abrahamsen et al.* 1976a, *Teigen et al.* 1976). The basic mechanical and chemical properties of the soil in the three experiments are similar (Tab. 1). In all experiments the soil is dominated by sand. Soil reaction is similar, as is the total nitrogen content. A basic sketch of the soil profiles is given in Figure 2.

The podzol-brown earth soil type (Nordmoen I, Tab. 1) is believed to be unstable and highly influenced by the forest vegetation. The forest on this site was clear-cut 15-20 years ago, at which time the profile probably was an iron podzol. The clearcutting and the subsequent change in the ground cover vegetation are believed to have produced a gradual change in the soil profile to the podzol-brown earth of today.

The ground vegetation in the podzol-brown earth experiment has a very dense layer of the grass *Deschampsia flexuosa.* In the other experiments, and in particular in the Scots pine experiment in Åmli, the ground vegetation is more sparse and less dominated by one species (Tab. 2).

The podzol lysimeter experiment is carried out with a soil very similar to that of the Norway spruce experi-

Fig. 1. Study area locations.

ment (Nordmoen II, Tab. 1). The area where these lysimeter cores were taken was clear-cut in 1973 and original climax vegetation is either dying out or being overrun by pioneer species. As of the autumn of 1975 much of the area was still free of vegetation (Tab. 4). The lysimeters with the podzol-brown earth have the same dense grass vegetation as the field plots on this soil type.

The lysimeters are 45 cm-deep fibre-glass cylinders filled with undisturbed soil monoliths with ground vegetation intact (Fig. 2). They are placed in the field and, like the field plots, are not sheltered from natural precipitation. The podzol-brown earth lysimeter experiment was started up in August, 1972 and supplied with 25 mm/month of water. The podzol series was started in June, 1974 and supplied with 50 mm/month of water. Lysimeters only receiving natural precipitation are included in the podzol series but not in the podzol-brown earth series. The lysimeter experiments have 2 replicates.

The field plot experiments, with plot sizes ranging from 15 to 150 m^2, have 3 replicates. The podzol-brown earth experiment, which was started in September, 1972, is treated with 25 or 50 mm/month of simulated rain. The podzol experiment with Norway spruce was started in June, 1973 and the Scots pine experiment in August, 1974. These two experiments are treated with 50 mm/month of simulated rain which is in addition to the natural rain, and applied once a month. The time used to apply 50 mm rain varies from 20 minutes to about 3 hours according to plot size and irrigation equipment. Most experiments include non-irrigated plots.

The monthly application of simulated rain is carried out in the frost-free period, usually five times a year. The irrigation water is obtained from ground water with the following chemical characteristics: pH 5.6 – 6.1, conductivity 20 – 40 μS/cm, Ca 1.2 – 3.7 mg/l, Mg 0.3 – 0.7 mg/l, Na 1.5 – 2.6 mg/l, K 0.3 – 0.7 mg/l, NO_3-N 0.08 – 0.22 mg/l.

The acidity of the simulated rain is adjusted by means of high quality sulphuric acid. The various experiments do not have identical treatments with respect to pH values, but all include pH 6 or 5.6, pH 4 and pH 3. Some

Table 1. Soil chemical characteristics of the field plot experiments.

Location	Soil profile	Soil texture	Soil chemical properties					
			Soil horizon	Loss on ignition %	N % of oven dry material	$pH_{(H_2O)}$	Cation exch. capacity me/100 g	Base saturation %
Nordmoen I	Podzol-brown earth	Clay 0%	0	28	0.60	4.4	39	25
		Silt 3 – 18% Sand 80 – 100%	A_{eh}	7	0.15	4.4	17	15
		Gravel 15%	B	4	0.07	4.7	11	7
Nordmoen II	Iron podzol	Clay 0%	0	63	0.90	4.3	73	21
		Silt 2 – 10% Sand 90 – 98%	A_e	5	0.10	4.3	15	8
		Gravel 0%	B	2	0.07	5.4	3	6
Åmli	Iron podzol	Clay 0%	0	87	1.6	3.7	135	15
		Silt 0% Sand 50 – 92%	A_e	3	0.08	4.5	7	5
		Gravel 8 – 50%	B	5	0.10	5.2	6	2

Soil samples were taken from the following approximate depths: O layer (humus layer), 0 – 3 cm; A layer, 3 – 6 cm; B layer, 9 – 16 cm. Chemical analyses carried out according to the procedure described by *Ogner et al.* 1975. Soil texture determined by dry sifting *(Abrahamsen et al.* 1976a).

experiments additionally include pH 2.5 and pH 2. The weighted mean pH of the simulated and natural rain together, which corresponds to pH 6, 4, 3, 2.5 and 2 of the simulated rain, are approximately 4.5, 4.2, 3.4, 3.0 and 2.5, respectively.

Soil samples for chemical and biological analyses were collected from the field plots in October and November, 1975, from 4 to 8 weeks after the last application of simulated rain. During this 4 to 8 weeks' period, about 100 mm of natural rain reduced the concentration of the previously applied dilute sulphuric acid.

The leachate of the lysimeters was analysed weekly for pH, conductivity and colour. The remainder was preserved with HCl and analysed monthly for other chemical properties.

The chemical analyses of soil and water were carried out according to the procedures described by *Ogner et al.* (1975). The base saturation was determined by extracting the soil samples with neutral 1 N ammonium acetate solution. The procedure implies that both water-soluble and exchangeable ions were determined.

3. Effects on vegetation canopies

When penetrating the vegetation, the composition of air and precipitation is altered due to interactions predominantly with the foliage. The foliage itself may be significantly affected by direct injuries and by leaching of nutrients.

Table 2. Characteristics of the vegetation of the field plot experiments (from *Abrahamsen et al.* 1976a).

Location	Trees			Ground vegetation	
	Species	Year planted	Average height (m) 1975	Vegetation type	Dominating species
Nordmoen I	Lodgepole pine *Pinus contorta* Dougl.	1965	3	*Eu-Piceetum Myrtilletosum*	*Deschampsia flexuosa* (L.) Trin.
Nordmoen II	Norway spruce *Picea abies* (L.) Karst.	1956	4	" "	*Deschampsia flexuosa*
Åmli	Scots pine *Pinus sylvestris* L.	1968 – 70	1.5	*Vaccinio Pinetum*	*Vaccinium vitis-idaea* L. *Deschampsia flexuosa* *Calluna vulgaris* (L.) Hull

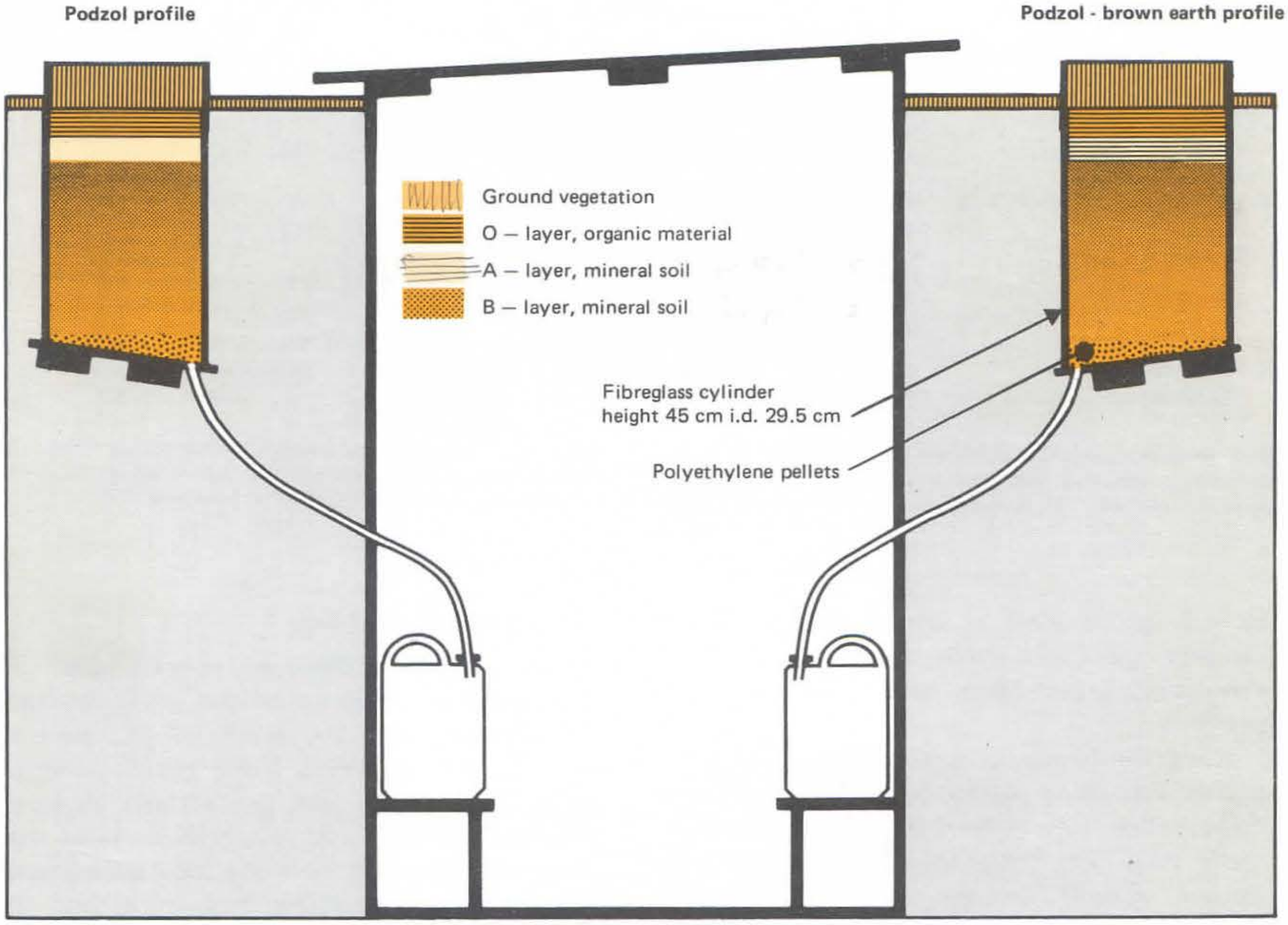


Fig. 2. Lysimeter design and sketch of soil profiles studied (from *Teigen et al.* 1976).

3.1. Throughfall studies

The objectives of the throughfall studies were both to describe the chemical quality of the precipitation which actually reaches the soil, and also to estimate the amount of dry deposition on different types of vegetation. The results have been published by *Bjor et al.* (1974) and *Horntvedt* & *Joranger* (1974, 1976). With regard to dry deposition, the results have also been interpreted by *Dovland et al.* (1976).

The studies were carried out at Birkenes in southern Norway, and at Målselv in northern Norway (Fig. 1). Some results from Birkenes are summarized in Table 3.

All types of vegetation at the Birkenes site absorbed nitrate and ammonium from the rain, with the conifers and Ericaceae absorbing most. This absorption seems to be a widespread but not general phenomenon (*Horntvedt* 1975).

In Målselv, no absorption of nitrogen by conifers was found (*Horntvedt* & *Joranger* 1974). This is quite likely due to the site being less oligotrophic and to the lesser amounts of epiphytes.

Table 3 shows that the throughfall under conifers was much more acid than the incident rain, whereas the throughfall under birch and ground cover vegetation was less acid. Birch stemflow, however, was more acid than incident rain.

The content of other ions was generally higher both in throughfall and stemflow. In Birkenes, the throughfall under conifers contained roughly twice as much chloride, sodium, and sulphate as did incident rain. This enrichment is probably the upper limit of what can be ascribed to washed off dry deposits at this location. However, the throughfall enrichment in magnesium, calcium, and potassium was still higher and must be partly due to leaching of excreted substances. A literature survey of similar studies showed that little is known about the relative importance of these two processes (*Horntvedt* 1975).

It should be noted that the analyses did not cover possible organic ions. This may explain the apparent deficiency of anions in our throughfall samples. The mean values of the ratio of anions

Table 3. Precipitation quality in open plots and beneath different kinds of vegetation.

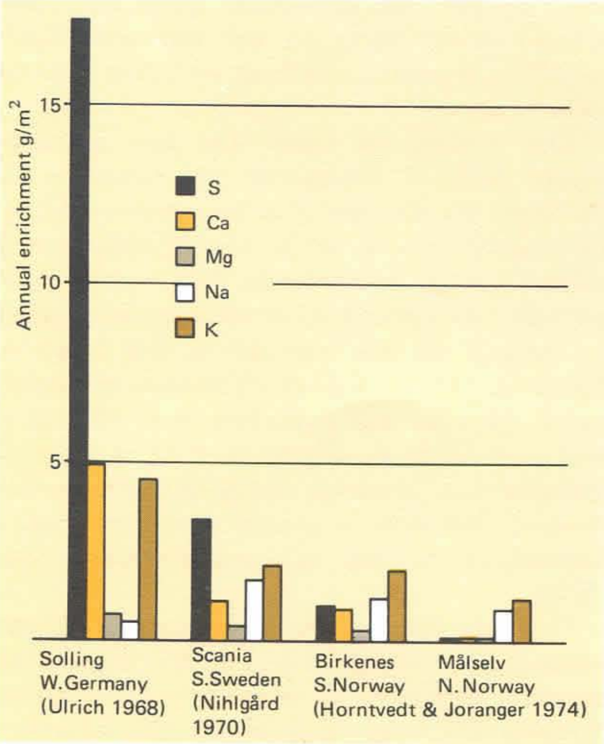
Plot	Period	Precip. mm	Cl	SO_4	NO_3	PO_4	Na	K	Ca	Mg	NH_4	H^+	pH weighted mean
			g/m²										
Open	May 28 – Oct. 5	550	1.3	1.6	0.8	0.0	0.8	0.1	0.1	0.1	0.2	0.03	4.3
Betula	"	440	2.1	2.1	0.4	0.0	1.2	0.8	0.4	0.2	0.1	0.02	4.5
Pinus	"	460	3.8	3.3	0.3	0.0	2.1	0.9	0.6	0.3	0.1	0.08	4.0
Picea	"	320	2.8	3.6	0.1	0.0	1.3	1.5	0.6	0.2	0.0	0.05	4.0
Open	July 7 – Oct. 13	500	1.4	1.5	0.8	0.0	0.8	0.1	0.1	0.1	0.2	0.03	4.3
Calluna	"	350	1.1	1.2	0.3	0.0	0.6	0.2	0.1	0.1	0.2	0.02	4.4
Vaccinum	"	400	1.4	1.6	0.3	0.1	0.7	0.6	0.2	0.1	0.0	0.02	4.5
Pteridium	"	440	2.0	1.4	0.5	0.2	0.6	1.2	0.2	0.2	0.1	0.01	4.9

Data from Birkenes 1974. Collection and analyses of daily samples under trees, and weekly samples under ground vegetation. The analyses cover the dissolved ions of the chemical components. H^+= titrated strong acid (see *Dovland et al.* 1976). pH weighted with precipitation quantity. Quantities are totals for the periods shown (from *Horntvedt* & *Joranger* 1976).

to cations in me/l at Birkenes were 1.0 in incident rain and 0.85, 0.79, and 0.69 in throughfall under birch, spruce, and pine, respectively.

When European throughfall studies are compared (Fig. 3), a pattern appears. The sodium values reflect the distance from the coast to the study areas. The larger increase from North to Central Europe of the other elements in throughfall, particularly sulphur, is probably mostly due to a parallel increase in the air pollution, cf. *Dovland et al.* (1976).

Fig. 3. Throughfall enrichment of some elements under spruce crowns at different locations in Europe.



3.2 Leaching from foliage

The results from Birkenes showed that the concentrations of metal cations in the throughfall increased with the acidity of the incident rain (*Bjor et al.* 1974, *Horntvedt* & *Joranger* 1974). In incident rain, the sea salt elements chloride, sodium, and magnesium made one group of correlated elements, and ammonium, nitrate, calcium, sulphate, and strong acid another. In throughfall, all elements except strong acid were correlated. The lack of correlation between strong acid and the other ions was most consistent beneath birch. This indicates that a cation exchange occurs in the tree crown, so that hydrogen ions replace other cations (*Eaton et al.* 1973).

To test the cation exhange hypothesis, throughfall under spruce crowns was analysed in one of the acidification experiments (Nordmoen II, Fig. 1). The "rain" pH significantly affected the amount of calcium, magnesium and potassium in throughfall (Fig. 4). From the water with low acidity, the tree crowns absorbed calcium and to a lesser degree magnesium. This experiment demonstrates that at the same level of dry deposition, the leaching is pH-dependent. *Wood* & *Bormann* (1975a) also found increased foliar leaching with lower pH in an acid mist. They ascribe this largely to foliar injuries, dead cells being more readily leached. In our experiments with spruce, no injuries are visible as yet.

3.3. Direct injuries

The highest risk for direct injuries on a regional scale in Norway seems to be from the deposition of acid particles. In addition, the risk of direct

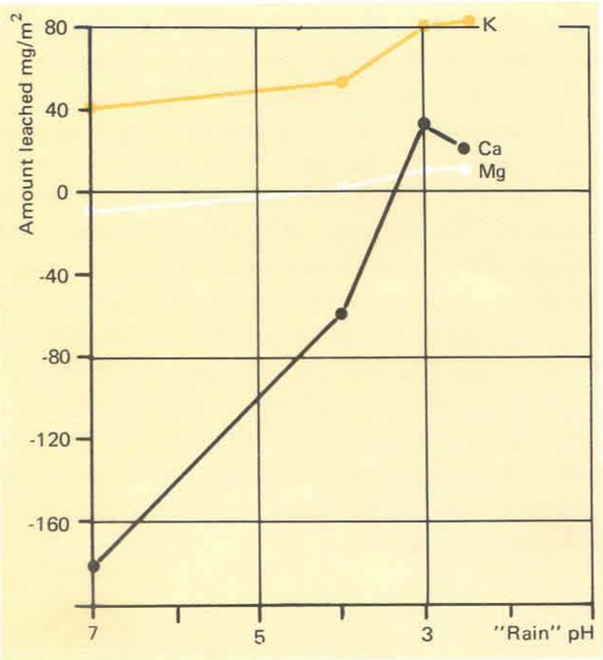


Fig. 4. Effect of pH of simulated rain on leaching of Ca, Mg and K from spruce crowns.

Average of two treatments with 50 mm "rain". Before passing the tree crowns, the "rain" contained 315, 35 and 35 mg/m^2 of Ca, Mg and K, respectively. Leaching of Na, NH_4, NO_3, Cl and PO_4 was not significantly dependent on "rain" pH.

sulphur dioxide injuries will be evaluated. Other pollutants are considered unimportant in this connection.

Injuries from acid rain and mist have recently been reported by *Wood & Bormann* (1974, 1975a) and *Shriner* (1975) at or below pH 3.0 - 3.2. *Striffler & Kuehn* (1975), however, noted no foliar symptoms at or above pH 2.

In our acidification experiments on field plots, foliar lesions, predominantly occurring as necrotic spots, were observed on birch (*Betula pubescens* Ehrh.), willow herb (*Chamaenerion angustifolium* (L.) Scop.), and Scots pine at pH 2 and 2.5, and on mosses at or below pH 3.0.

Table 4. Vegetation cover on podzol lysimeters as affected by pH of simulated rain.

Treatment	Number of species	Per cent cover: Field layer	Moss layer	Bare soil (litter)
(No watering)	9	50	0	50
pH 6	9	40	15	45
pH 4	7	20	10	70
pH 3	6	33	0	67
pH 2	5	13	0	87

Observations following 7 monthly treatments (3 in 1974 and 4 in 1975) with 50 mm of simulated acid rain in addition to natural precipitation (from *Teigen et al.* 1976).

Effects were also recorded on the ground cover in one of the lysimeter experiments *(Teigen et al.* 1976). With increasing acidity of the artificial rain, both the number of species and the per cent cover of the field layer decreased (Tab.4).In unwatered lysimeters the mosses (mainly *Pleurozium schreberi* (Willd.) Mitten) became desiccated and partly died out, but they also died out in treatments with water of pH 2 and 3.

It is probable that, besides species susceptibility, the stage of cuticle development and the spray or mist intensity are important factors in determining the threshold value of injurious pH of the precipitation. The "rain" intensity in our field experiments is very high. Mist experiments in growth chambers may well demonstrate that the same plants are more sensitive to low pH.

Regarding sulphur dioxide injuries to trees, *Tamm & Aronsson* (1972) provided a very useful compilation of sulphur dioxide concentrations and exposure times which have been used in experiments or measured in field surveys. For exposures of a few hours, the threshold values for slight injury lie in the range of 0.1 to 1.0 mg/m^3, the lowest values being confined to selected sensitive clones of *Pinus strobus* (L.). For exposures of months or years threshold values in the range of 0.05 – 0.1 mg SO_2/m^3 have been postulated (*Knabe* 1971).

In southernmost Norway (Birkenes), 24-hour mean sulphur dioxide values above 0.03 mg/m^3 are rather uncommon and only occur during episodes of a few days (*Dovland et al.* 1976). The risk of sulphur dioxide injuries to trees on a regional scale therefore seems to be very low at present, and such injuries have not been observed.

Epiphytic lichens are very sensitive to many types of air pollutants. From the studies of *Hawksworth & Rose* (1970) in England, a mean winter concentration of 0.03 mg SO_2/m^3 is indicated to be the threshold value for injuries to lichens. It was also noted that some lichen species normally restricted to trees with acid bark (conifers) have become more common on deciduous trees, probably due to acidification of the bark (*Hawksworth et al.* 1973).

There is no evidence of significant injuries to lichens in Norway aside from sources of local pollution. For example, in Birkenes, lichen growth on trees is luxuriant. However, no critical regional studies have been undertaken.

3.4. Interactions with insects and pathogens

There are reasons to believe that some pathogens and insects can be favoured, and others disfavoured, by acid precipitation. Around sources of local pollution there are many indications of such interactions (*Donaubauer* 1966). Determinant factors can be the increased deposition of substances during dry periods, increased wash-off and leaching of foliage by acid rain, erosion of the cuticular waxes that protect the leaf (*Shriner* 1975), and the general stress produced on the plant.

In southernmost Norway, the pine bud moth (*Exoteleia dodecella* (L.)) has caused severe damage to about 250 km^2 of Scots pine forests during the last five years (*Hågvar et al.* 1976). The injury has occurred in the same areas of Norway which receive the largest quantities of air pollutants transported over long distances.

In Poland, where this pest is more common, the attacks of the pine bud moth are most intense and persistent in areas which are influenced by sources of local pollution (*Sierpiński* 1962). Extensive attacks by this insect have not been recorded in Norway, except for one case near an industrial center. Because the distribution of the present attack cannot be explained by local pollution, the hypothesis is presented that long-range transport of air pollutants may have weakened the health of the trees, creating favourable conditions for the insect (*Hågvar et al.* 1976).

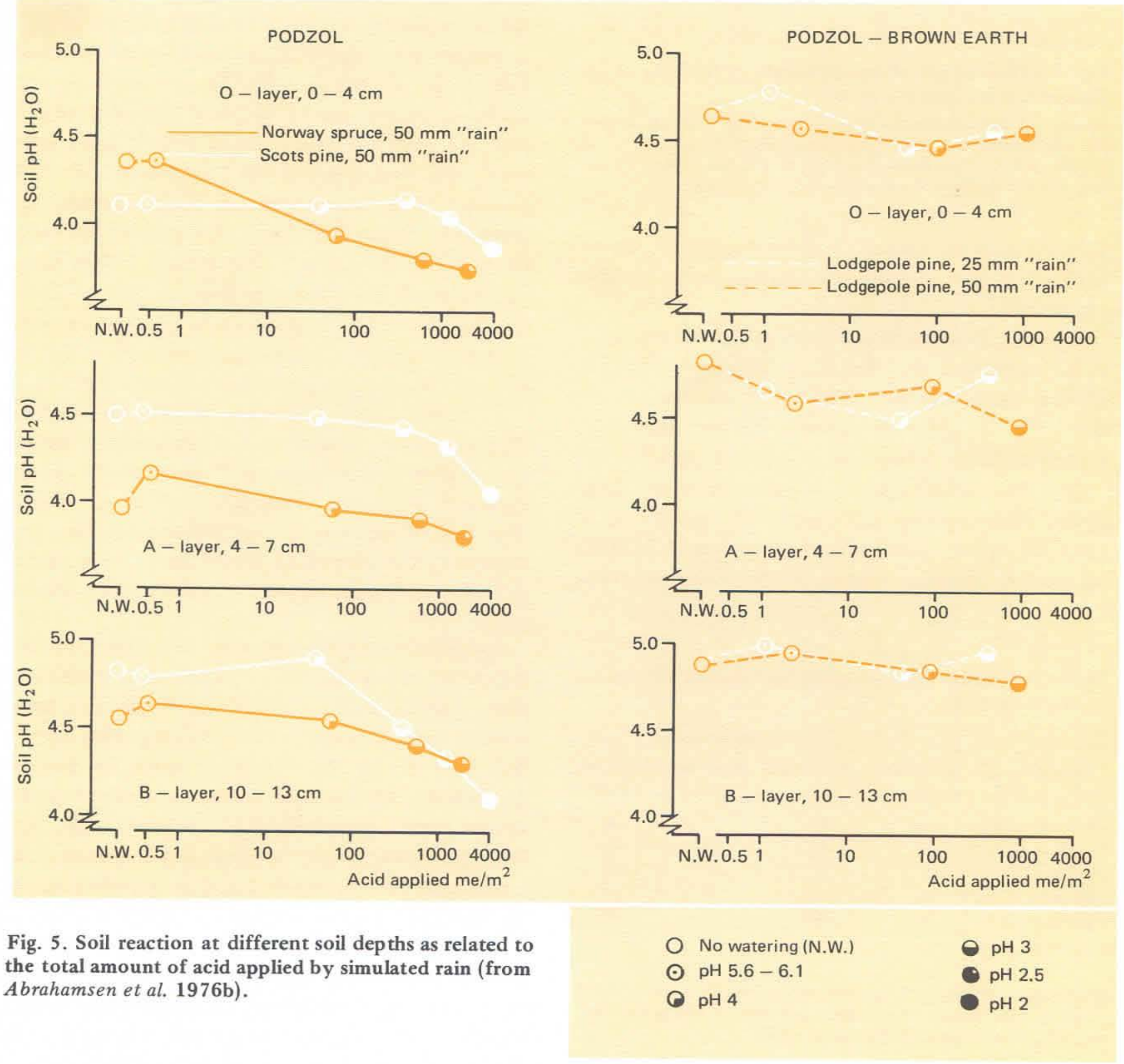


Fig. 5. Soil reaction at different soil depths as related to the total amount of acid applied by simulated rain (from *Abrahamsen et al.* 1976b).

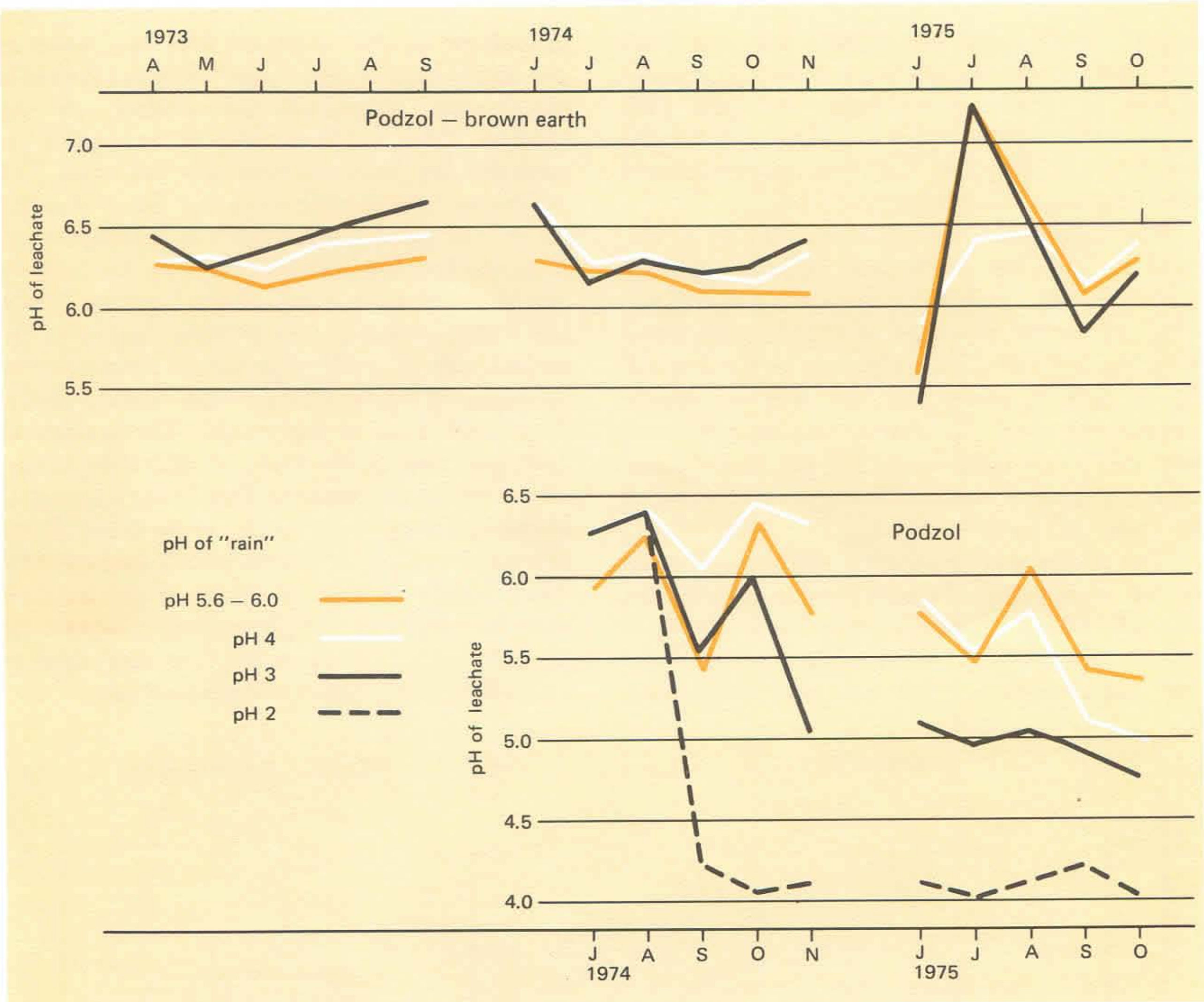


Fig. 6. pH fluctuations in the leachate from the lysimeters. Figures based on weekly observations in the frost-free period of the year (from *Teigen et al.* 1976).

4. Effects on soil

Soil is a complex system governed by chemical, physical and biological reactions. Effects of acid precipitation may be varied, including changes in the distribution and leaching of nutrients from the soil, changes in the rate of mobilization and mineralization of plant nutrients by weathering and decomposition processes, and change in the competion for nutrients by various soil organisms (immobilization processes) (*Likens* & *Bormann* 1972, *Malmer* 1973).

It has not been possible to study all these aspects, but efforts have been made to accomplish studies on some of the processes considered to be most important to the supply of plant nutrients.

4.1 Soil chemistry

Increased loss of plant nutrients from soils is one of the most serious potential effects of acid precipitation on terrestrial ecosystems. In general, this potential loss is considered insignificant in most agricultural soils where the buffer capacity is high and nutrients are regularly replaced (*Odén* 1968, *Sorteberg* & *Ødelien* 1971, *Reuss* 1975). In forest soils, on the other hand, increased loss of nutrients may be of importance in the long run (*Odén* 1968, *Overrein* 1972, *Reuss* 1975).

Changes in the nutrient pool in the soil were studied by means of experiments with simulated acid rain in field lysimeters (*Teigen et al.* 1976). These experiments have so far been restricted to leachate analyses, and redistribution of nu-

trients within the soil system has not been examined. Such changes were studied in part by means of soil samples from the field plot experiments with simulated acid rain (*Abrahamsen et al.* 1976b). The field experiments are not sheltered from natural precipitation.

The application of simulated acid rain to the field plots did not significantly influence the soil acidity in the podzol-brown earth experiment (Fig. 5). In the two podzol experiments, however, the soil pH was significantly reduced in the O, A and B layers. In the Norway spruce experiment even the lowest concentration of acid (pH 4) has reduced the soil pH. In the Scots pine experiment soil reaction was only affected by "rain" pH levels below 3.

The different influences on the two soil types by the application of acid were also observed on the pH values of the leachate from the lysimeters (Fig. 6). The acidity of the leachate from the podzol-brown earth was not noticeably influenced by the simulated acid rain, whereas the application of acid "rain" to the podzol soils significantly increased the acidity of the leachate. Even treatment with water of pH 4 has acidified the leachate from this soil type. The difference between the two soil types is illustrated by the output/input ratio of hydrogen ions from the lysimeters (Figs. 8 and 9). The ratio in the podzol-brown earth varies between 0.001 and 0.006, whereas it is 10 times higher in the podzol soil. In both experiments there tend to be relatively more hydrogen ions retained at low "rain" pH than at higher pH. The output of hydrogen ions is, however, calculated by means of the pH in the leachate. Due to the content of aluminium ions in particular, (Figs. 8 and 9) the titrateable acidity of the leachate is undoubtedly much higher at low pH levels of the leachate than that given by the pH readings. The amount of aluminium leached at pH 2 is equivalent to about 85% of the input of hydrogen ions.

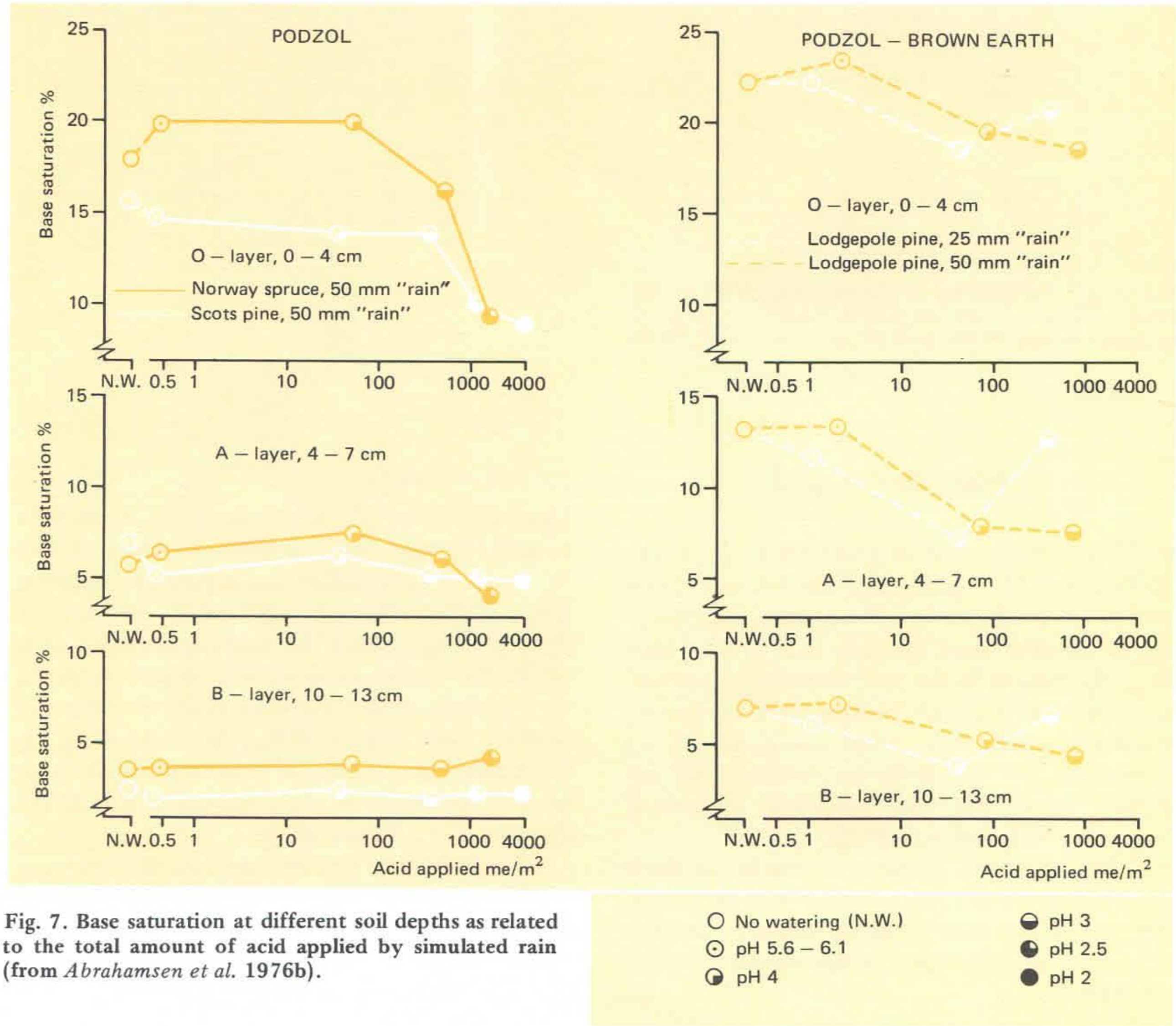


Fig. 7. Base saturation at different soil depths as related to the total amount of acid applied by simulated rain (from *Abrahamsen et al.* 1976b).

Table 5. Effect of simulated acid rain on the content of extractable metal cations in the soil of the field plot experiments (me/100 g).

Experiment	Soil layer, approx. sample depth, cm	Elements	pH of simulated rain				
			5.6 – 6.0	4	3	2.5	2
PODZOL-BROWN EARTH (Lodgepole pine, Started Aug. 1972)	O – layer (0 – 4 cm)	Σ Na, K	0.78	0.73	0.99		
		Σ Ca, Mg, Mn	8.69	4.95	6.70		
	A_{eh} – layer (4 – 7 cm)	Σ Na, K	0.20	0.21	0.19		
		Σ Ca, Mg, Mn	1.87	1.07	1.06		
IRON PODZOL (Norway spruce, Started June 1973)	O – layer (0 – 4 cm)	Σ Na, K	1.51	1.74	2.01	1.46	
		Σ Ca, Mg, Mn	8.09	11.12	10.28	3.82	
	A_e – layer (4 – 7 cm)	Σ Na, K	0.17	0.50	0.16	0.17	
		Σ Ca, Mg, Mn	0.66	0.86	0.67	0.38	
IRON PODZOL (Scots pine, Started June 1974)	O – layer (0 – 4 cm)	Σ Na, K	1.25	1.10	0.94	1.06	0.91
		Σ Ca, Mg, Mn	19.50	17.00	16.65	13.63	11.25
	A_e – layer (4 – 7 cm)	Σ Na, K	0.10	0.09	0.11	0.09	0.08
		Σ Ca, Mg, Mn	0.27	0.25	0.37	0.26	0.25

Non-irrigated plots, i.e., those only receiving natural precipitation, and plots irrigated with 25 mm/month (the podzol-brown earth experiment) are not included since these "treatments" have no noticeable effect on the content of cations in the soil. The proportion of individual elements in the soil has not been influenced by the treatments. Of the total content of cations (me) in the O-layer, Ca constitutes 50 – 75%, Mg 12 – 25%, Mn 1 – 15%, K 4 – 25% and Na 1 – 2%. In the A-layer the proportions are: Ca 43 – 70%, Mg 11 – 30%, Mn 0 – 13%, K 8 – 35% and Na 1 – 14% (from *Abrahamsen et al.* 1976b).

The varying effect of acid application on soil reaction is likely to be reflected by the content of exchangeable cations in the soil and by the base saturation. The content of exchangeable cations is quite variable. Despite this a significant decrease in the amount of individual ions was observed for calcium, magnesium and manganese in the two podzol experiments (Tab. 5). In the Norway spruce experiment significant decreases were only found from "rain" pH 3 to "rain" pH 2.5. In the Scots pine experiment, on the contrary, even "rain" of pH 4 decreased the content of divalent ions compared with the control plots. There is also a tendency, although not significant, for the content of monovalent cations in the upper soil layer to be reduced by the application of acid.

The reduction in the base saturation, which concerns all major cations, is more conspicuous than the reduction in the content of individual cations (Fig. 7). At the plots receiving 25 mm/month of "rain" in the podzol-brown earth experiment, however, no significant trend in the base saturation was found. The application of 50 mm "rain" of pH 3, on the other hand, significantly reduced the base saturation in all three soil layers ($P < 0.01$). The reduction is smaller than that observed in 1974 (*Abrahamsen et al.* 1975), but this can most likely be ascribed to random variations. In the podzol experiment with Norway spruce, significant reductions in base saturation in the O and A layers were found with application of water at pH 4 or below. The base saturation in the Scots pine experiment was only significantly influenced in the humus layer and only by "rain" more acid than pH 3.

Differences in leachate acidity between the two lysimeter experiments also reflect differences in the nutrient budgets (Figs. 8 and 9). The budgets given are weighted annual means for the experimental periods. The annual means have not varied significantly, but there are large seasonal fluctuations in the loss of nutrients. As the concentrations are independent of the amount of leachate, the seasonal fluctuations mainly reflect variations in waterflow.

With the exception of calcium, the net loss of ions from the podzol-brown earth is much smaller than from the podzol soil. In the podzol-brown earth lysimeters net losses are found for calcium, magnesium and aluminium. In the podzol lysimeters net losses are additionally found for manganese, sodium, potassium, iron, and in some cases, for nitrate. The leaching of nitrate and ammonium from the podzol lysimeters is, however, not consistent and general statements cannot be made. In the podzol-brown earth lysimeters mineral nitrogen is re-

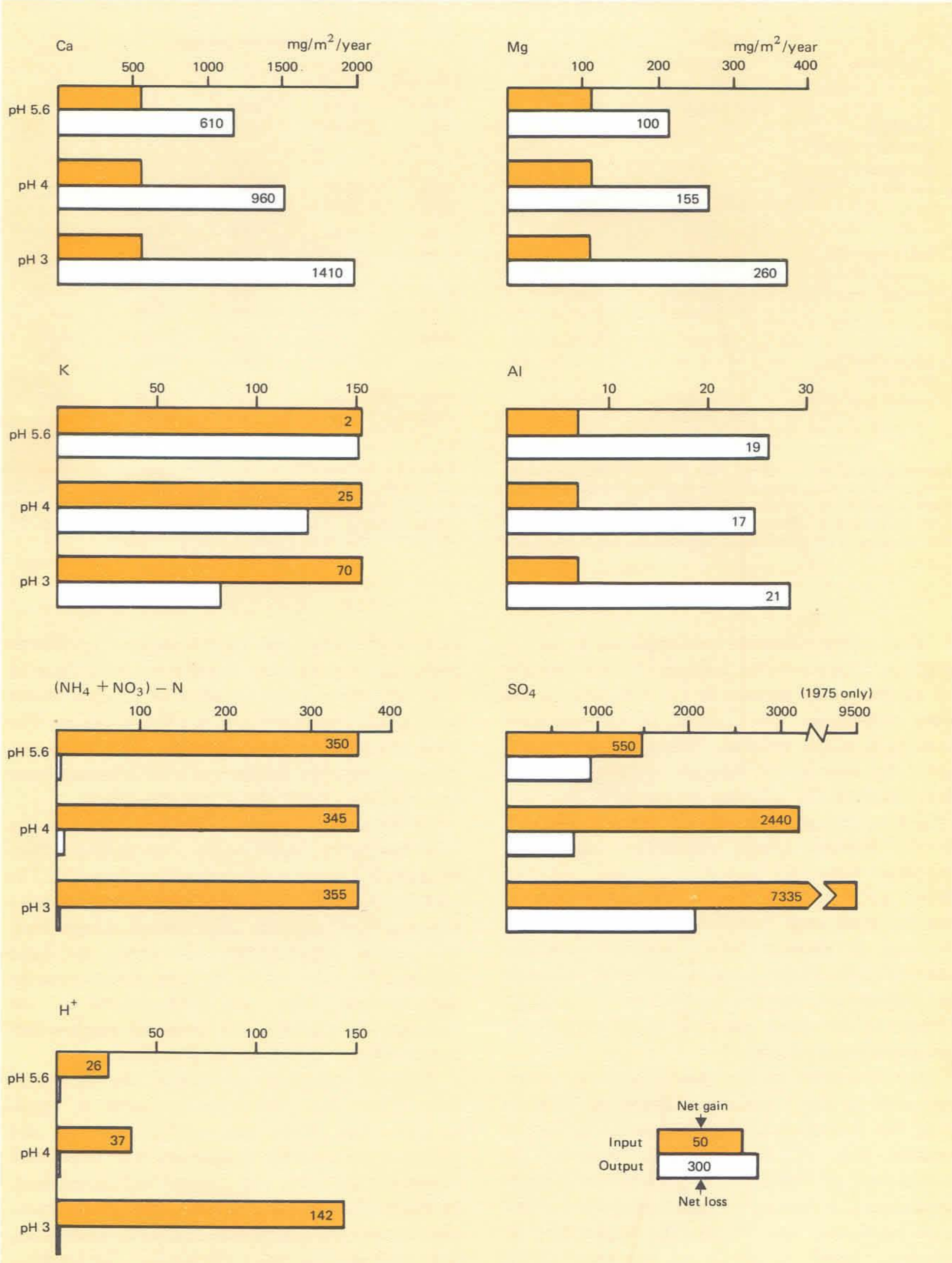


Fig. 8. Nutrient budgets of the podzol-brown earth lysimeters as related to the pH of the simulated rain (from *Teigen et al.* 1976).

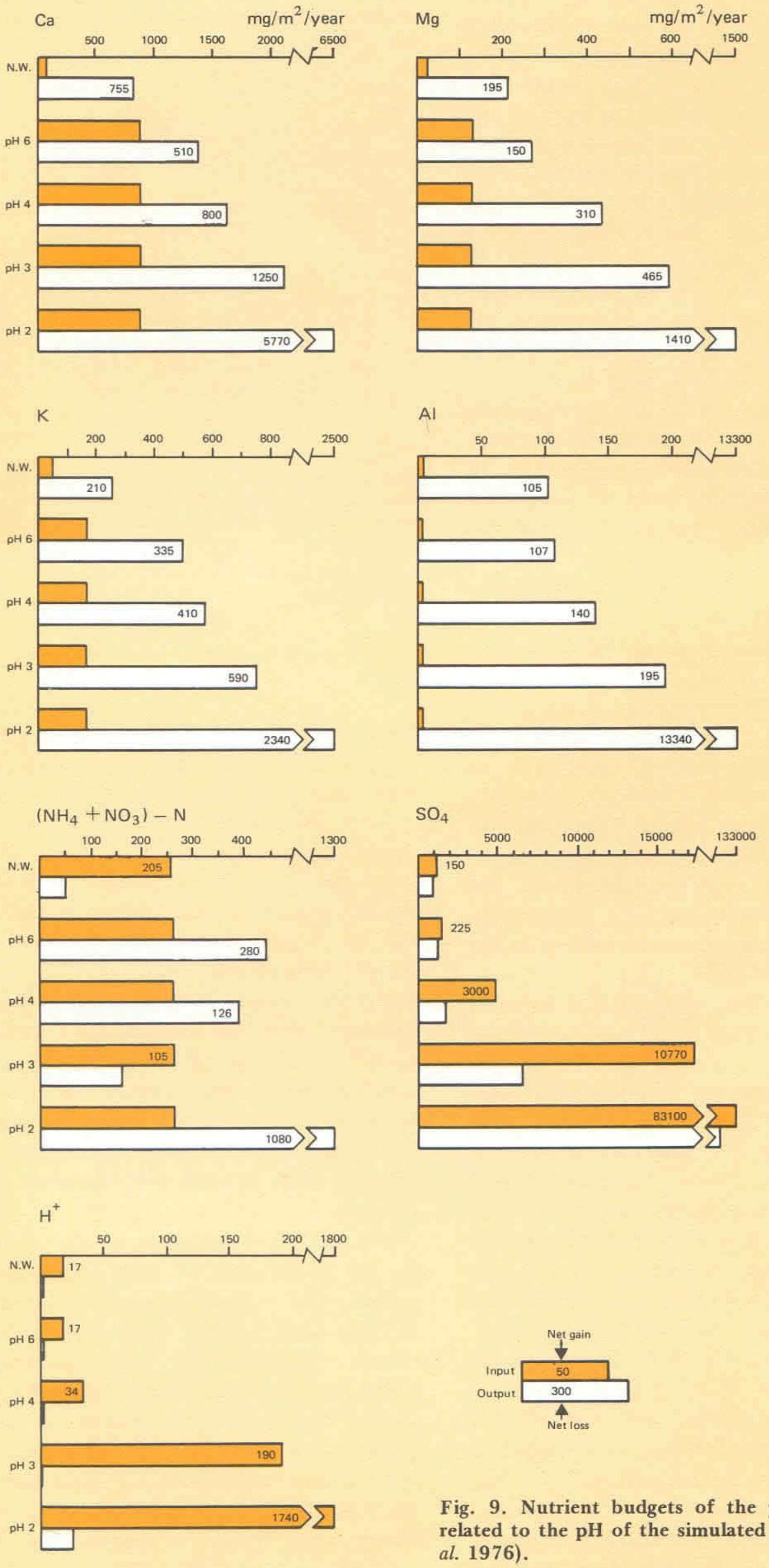


Fig. 9. Nutrient budgets of the podzol lysimeters as related to the pH of the simulated rain (from *Teigen et al.* 1976).

tained in the soil. No evidence has been found that the content of mineral nitrogen in the soil is influenced by the application of acid.

The net loss of calcium and magnesium increased 50 to 110% when the acidity of the "rain" was increased from pH 5.6 or 6 to pH 4. If the pH of the "rain" dropped from 5.6 or 6 to pH 3 the net loss increased 130 to 230%. The non-watered lysimeters, which only received natural precipitation with an average pH of about 4.4 (*Dovland et al.* 1976), had a considerably higher net loss of calcium and magnesium than those additionally receiving 50 mm/month of non-acidified water. The large increase in leaching of aluminium from the podzol lysimeters by increased application of acid is directly related to the acidity of the leachate (Fig. 6). This explains the large amounts of aluminium leached from the podzol soil compared with the podzol-brown earth.

Net loss of nutrients should be viewed in relation to the total content of exchangeable ions in the soil. Table 6 shows that the non-watered soil of the podzol series has annually lost between 1 and 5% of the original amount of exchangeable cations. The watered control lysimeters have lost slightly less, and those watered with "rain" of pH 4 have lost between 2 and 8%. Further increase in "rain" acidity has significantly increased the relative losses, in particular of calcium, magnesium and manganese. In the podzol-brown earth experiment the relative losses of calcium and magnesium are similar to the losses from the podzol soil.

The increased leaching of particular nutrient elements and the decrease in the base saturation with increasing acidity of the percolating soil solution support previous results from Norwegian soils (*Overrein* 1972, *Abrahamsen et al.* 1975, *Haugbotn* 1976). *Tamm et al.* (1975) found, as in the present study, increased acidity of the leachate from acidified lysimeter soils but, in contrast to our study, small changes in the leaching of plant nutrients. This result supports the theories launched by *Wiklander* (1973/74, 1975), who calls attention to the low efficiency of hydrogen ions in exchanging metal cations in acid (pH < 5-5.5) podzol soils. *Wiklander* (1973/74) concludes that the adverse effects of acid precipitation are "very slight" in podzol soils with a low base saturation (2 - 20%) and a pH often less than that of the precipitation. This conclusion is supported by *Bergseth* (1975) who found significantly less leaching

Table 6. Annual net loss of elements as percentage of the total amount of exchangeable ions in the lysimeter soils (from *Teigen et al.* 1976).

Experiment and treatment	Ca	Mg	Mn	K	Na
Podzol-brown earth					
pH 5.6	2.7	3.5	− 0.8	− 0.03	− 4.1
pH 4	4.3	5.5	1.5	− 0.2	− 0.7
pH 3	6.5	9.3	0	− 0.7	1.4
Podzol					
no watering	3.9	4.8	1.3	1.0	–
pH 6.0	2.6	3.7	2.6	1.6	3.6
pH 4	4.1	7.6	2.0	1.9	6.6
pH 3	6.4	11.4	8.9	2.8	5.7
pH 2	29.7	34.5	52.4	11.0	21.5

Total amount (me/m^2 to 40 cm soil depth) of exchangeable elements in the lysimeter soils. Estimates based on soil samples taken concurrently with the establishment of the lysimeters.

	Ca	Mg	Mn	K	Na
Podzol-brown earth	1090	235	70	275	100
Podzol	970	335	170	545	100

from podzols than from brown earths. Little leaching was also observed as a result of soil acidification in podzolic profiles in the U.S.A. (*Cole* & *Johnson* 1974, *Johnson* & *Cole* 1975).

The results presented in the present paper reveal that the effect of acid was smaller in the soil designated as podzol-brown earth than in the iron podzol soil. Since both soils are coarse-textured and free of clay, this result might be unexpected. It should be stressed, however, that the designation "podzol-brown earth" on the soil of the lodgepole pine experiment might be misleading. The profile most probably is a result of the clear-cutting 15-20 years ago and the soil can be expected to develop into an iron podzol when the forest matures.

The different responses of the two soil types to the application of acid might have several causes. The different amounts of water, and thereby acid, applied have already been mentioned. However, the most important factor might be the difference in ground cover vegetation. The dense grass growth on the podzol-brown earth has probably efficiently retarded the leaching by consuming water and dissolved nutrients. The evapotranspiration in the podzol-brown earth lysimeters amounts to about 550 mm/year or about 70% of the input of water. In

the podzol lysimeters the evapotranspiration is about 200 mm/year or about 35% of the input of water. The water consumption of vegetation has otherwise been well documented by *Hoover* (1944), *Hibbert* (1967) and *Likens et al.* (1970). If this effect is as important as assumed, it means that the impact of acid precipitation on soil depends very much on the health and growth of the vegetation and thereby on its water consumption.

In conclusion, the main problem of this study lies in evaluating the results obtained. Even though rainfall with pH as low as 2.1 has occurred (*Likens* & *Bormann* 1974) and throughfall water is often more acid than incident rain (Tab. 3, and *Haugbotn* 1976), effects of simulated rain with pH below 3 should be viewed with caution. It is also likely that the effect of "rain" of pH 3 applied in a quantity of 250 me/m^2 /year of hydrogen ions is not directly comparable to the effect of the same deposition distributed over a 4 to 6 year period (annual deposition 40-60 me/m^2 /year). However, in some areas of southern Norway almost 10% of the total precipitation has a pH lower than 4.0 (*Dovland et al.* 1976). It should also be remembered that the weighted mean pH of the natural and simulated rain together is different from the pH of the simulated rain alone. These weighted means of the simulated rain plus the natural rain are calculated to be 4.5, 4.2, 3.4, 3.0 and 2.5 while the corresponding values of the simulated rain alone are 6, 4, 3, 2.5 and 2.0. Therefore, the effects of simulated rain of pH 3 and even pH 2.5 might not be unrealistic compared to natural rain. In addition, the simulated rain in use has a higher content of dissolved salts than the precipitation. Neutral salts in the percolating soil solution are likely to reduce the effect of acidification on the soil (*Wiklander* 1975). Therefore, it is unlikely that the effect of a certain concentration of acid has been overestimated in this study.

4.2. Soil biology

It is generally assumed that the rate at which various important microbial processes occur is lower in acid than in neutral soils. Many potential decomposer organisms, for example, are inactive or less active when the pH is much below 5 (*Williams* & *Gray* 1974). Various studies have shown that the rate of cellulose decomposition is lower in acid than in less acid and neutral soils (*White et al.* 1949, *Schmidt* & *Ruschmeyer* 1958). Studies in freshwater have similarily demonstrated retarded decomposition of birch leaves in acidified water (*Leivestad et al.* 1976).

Nitrogen fixation and nitrogen mineralization are other processes which apparently are related to soil reaction (e.g. *Alexander* 1967). Biochemical processes within the nitrogen cycle are of special importance in boreal conifer forests where nitrogen is a limiting factor for tree growth (e.g. *Tamm* 1975).

Decomposition and mineralization are mainly carried out by microorganisms, but soil animals may also significantly influence the rate of these processes (e.g. *Macfadyen* 1963, *Witkamp* 1971). The relationship between soil acidity and the activity of soil animals is little known, but groups like protozoa and earthworms are very rare in soils with pH below about 4 (*Stout* & *Heal* 1967, *Satchell* 1967).

For the reasons mentioned above, reduced biological activity in soil is a possible effect of acid precipitation (*Odén* 1968, *Malmer* 1973, *Tamm et al.* 1975).

4.2.1 Soil microbiology

Studies of soil microbial processes were restricted to decomposition of organic material, nitrification and nitrogen fixation.

Decomposition studies were performed on pine needles, on commercial cellulose sheets and on undipped aspen match-sticks. Withered, brown needles for decomposition studies were collected from the trees of the lodgepole pine experiment (Tab. 2) one and two years after the application of simulated acid rain had begun (*Abrahamsen et al.* 1975). The needles were incubated at 15 and 25°C on moistened glasswool. Weight loss after 90 days was measured as an estimate of decomposition. The application of acid "rain" (pH range 5.6-3) did not influence the decomposition rate.

Decomposition was also examined on lodgepole pine needles moistened with dilute sulphuric acid. This experiment, which was also ran for 90 days, revealed that the decomposition rate was significantly increased ($P < 0.05$) when the pH of the solution increased from 1.8 to 3.5. No difference was found between pH 3.5 and 4. At pH 1 no decomposition took place.

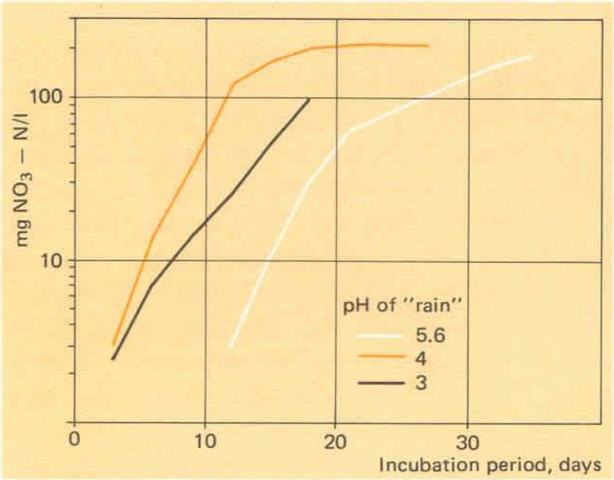


Fig. 10. Nitrification rate in soil samples from limed plots in the podzol-brown earth experiment with simulated acid rain.

Experiment carried out at 20°C using a perfusion technique with the addition of $(NH_4)_2SO_4$. The first linear phase of the curves shows the exponential growth of the nitrate-producing bacteria. The apparent generation times calculated for this phase are 50, 42 and 70 hours for soils treated with "rain" of pH 5.6, 4 and 3, respectively (from *Hovland* & *Ishac* 1975).

Decomposition of match-sticks and cellulose sheets placed on the ground in the field plot experiments was not consistently influenced by the application of simulated acid rain (*Hovland* & *Abrahamsen* 1976). In one experiment the decomposition of cellulose was significantly retarded by increased "rain" acidity, but in the other experiments no effect has so far been found.

Nitrification was studied in the laboratory on humus samples collected from the podzol-brown earth experiment (Tab. 1) (*Hovland* & *Ishac* 1975). The study was carried out using a perfusion technique with the addition of ammonium sulphate. Nitrate was only found in negligible amounts even though nitrifying bacteria were found in all soil samples. The lodgepole pine experiment does, however, also include some limed plots. On these plots simulated acid rain of pH 4 stimulated the production of nitrate, but further increase in the acidity seemed to reduce the nitrification rate (Fig. 10).

Studies on nitrogen fixation (*Hovland* 1976) were aimed at answering two questions: What is the magnitude of nitrogen fixation in Norwegian conifer forest soils, and how is it influenced by simulated acid rain? The studies were based on the acetylene reduction method. Soil samples including the moss layer were collected from various vegetation types including eutrophic and oligotrophic soils.

The nitrogen fixing activity was very low, in most samples below detectable quantities. No differences in fixation were found between rich and poor soils. The nitrogen fixation in the field experiments was also negligible, and no difference was found among the various treatments.

The general opinion that decomposition is likely to be retarded by acidification is mainly based on the observation that decomposition proceeds more readily in neutral than in acid soil. Experimental acidification of soil has, however, also been found to reduce the rate of cellulose decomposition (*Ruschmeyer* & *Schmidt* 1958).

Variation in soil acidity is, to a great extent, explained by base saturation which, therefore, may influence the decomposition rate (*Jorgensen* & *Wells* 1973). It has been found, for example, that litter from base-deficient raw humus sites has a higher content of polyphenols than litter from base-rich mull sites (*Coulson et al.* 1960). High contents of polyphenols in litter seem to stabilize leaf proteins and retard decomposition (*Davies et al.* 1964).

The studies referred to indicate that reduced decomposition is a consequence of soil acidification. Therefore, they do not explain the results reported by *Abrahamsen et al.* (1975) and *Hovland* & *Abrahamsen* (1976). However, these studies represent scattered experiments with a few selected materials and soil types that initially were very acid. They have also been running for only a relatively short period of time.

Tamm et al. (1975) observed that the carbon dioxide evolution in samples from forest soil was reduced by acidification of the samples. Decreased carbon dioxide evolution was accompanied by increased ammonification but reduced nitrification. They concluded that acidification of the soil had decreased the microbial activity, but the decrease was more pronounced for immobilization processes than for decomposition processes. The results obtained by *Hovland* & *Ishac* (1975) indicate that net nitrification is very small in the soil examined. It should be pointed out, however, that the factors influencing nitrate production seem to be only partly understood. In a beech forest soil with pH about 3, very small numbers of nitrite and nitrate-forming organisms were found (*Niese* 1971). In that soil, however, substantial amounts of nitrate were produced (*Runge* 1971). In highly acid soils the possibility of heterotrophic nitrification cannot be excluded.

In the soil studied by *Runge* (1971), only low numbers of free-living nitrogen-fixing organisms were found. This is in accordance with the low nitrogen fixation observed in Norwegian conifer forests (*Hovland* 1976). In a Swedish conifer forest, nitrogen fixation was estimated to be about 2 kg N/ha/year (*Lindberg* pers. comm.). Compared to the dry and wet deposition of mineral nitrogen, between 5 and 10 kg N/ha/year in southern Norway (calculated from *Dovland et al.* 1976), nitrogen fixation apparently is of limited importance in Norwegian conifer forests.

4.2.2 Soil zoology

The soil fauna in the podzol soils of Nordic conifer forests are numerically dominated by small animals such as mites (Acarina), springtails (Collembola) and enchytraeids (Oligochaeta). Larger animals, like earthworms, are very rare. The abundance of mites, springtails and enchytraeids is under study in the field plot experiments (*Hågvar* & *Abrahamsen* 1976). At present only figures from two experiments, and only for enchytraeids, are available.

Consistent results from the treatments on population density of various enchytraeid species were not obtained. The extreme variability of the density estimates is illustrated for the species *Cognettia sphagnetorum* (Vejd.) (Fig. 11), which is the dominating enchytraeid species in acid raw humus habitats (*Nurminen* 1967, *Abrahamsen* 1972).

The figures from the podzol experiment indicate a population increase when the amount of hydrogen ions applied increases from 0.5 me to 55 me ($P < 0.1$). Further application reduced the population density. In the podzol-brown earth experiment no similar effect was observed. The apparent disagreement between the results of the two experiments cannot be explained, but the soils of the two experiments are slightly different and so is the influence of simulated acid rain on the soil chemical properties (Tab. 5, Figs. 5 and 7).

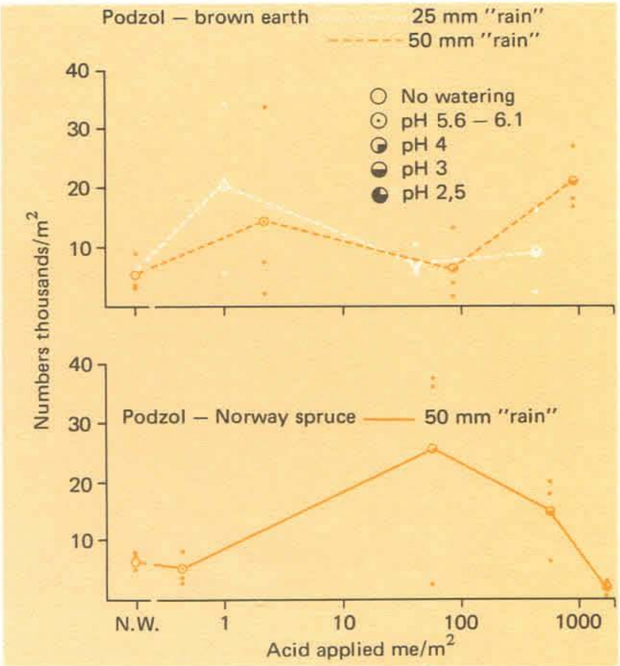


Fig. 11. Numbers of *Cognettia sphagnetorum* (Enchytraeidea, Oligochaeta) in some of the field plot experiments with simulated acid rain.

Circles denote means, dots denote individual observations. Sampling and extraction follows the procedure used by *Abrahamsen* (1972) (from *Hågvar* & *Abrahamsen* 1976).

5. Effects on growth

Effects of acid precipitation on soil and vegetation may influence growth and development of trees. Our studies include greenhouse experiments with seed and seedlings, regional investigations of past diameter growth and growth measurements in field acidification experiments.

5.1 Germination and seedling establishment

Soil acidity may influence seed germination and seedling establishment as indicated in earlier experiments (*Aaltonen* 1925, *Eneroth* 1931, *Bjerkestrand* 1970). Possible harmful influences of acid precipitation on germination and seedling establishment in mineral soil have been pointed out by *Ulrich* (1975).

Germination and seedling establishment of Norway spruce and Scots pine were studied in artificially acidified mineral soil (*Teigen* 1975, *Abrahamsen et al.* 1975). Soil acidity had a moderate influence on germination and seedling establishment at pH values greater than 4.2 – 4.4 (Fig. 12). At lower pH values negative effects occurred, most pronounced for seedling establishment. About 80% of the seeds did not

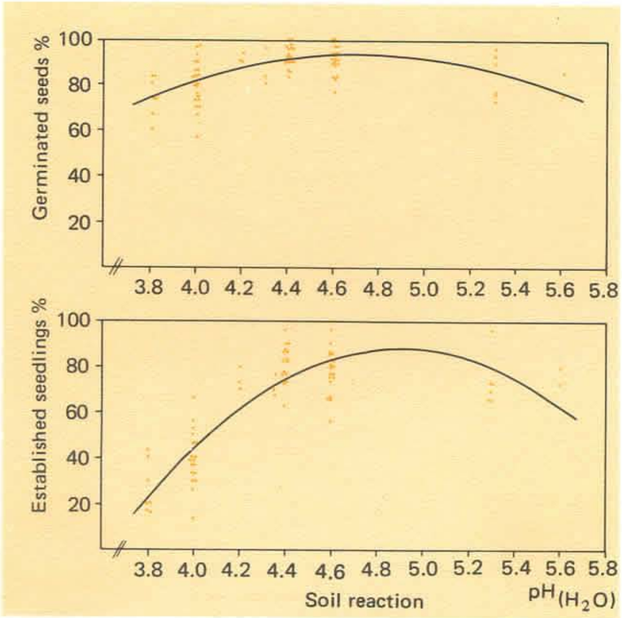


Fig. 12. Seed germination and seedling establishment of spruce related to soil reaction.

The curves show second-degree polynomials estimated by standard regression analysis with no significant "lack of fit". Soils of different acidity were obtained by percolating mineral soil with water acidified by sulphuric acid. Additional soil pH levels were obtained by liming. An adequate moisture regime was maintained after sowing by adding distilled water. Germination and seedling establishment were studied after 7 weeks (from *Teigen* 1975).

develop normal seedlings at pH 3.8. These results agree well with those of *Venn* (1966), who found no regeneration of Scots pine around a pyrites mining works when soil pH was 3.8 or lower.

Adverse effects on germination and seedling establishment in mineral soil may occur when acid precipitation actually lowers the soil reaction in the topmost layer of naturally acid soils.

Forest regeneration in Norway has shifted more to planting, but natural regeneration still comprises 20 – 25% of the yearly regeneration area *(Statistisk Sentralbyrå* 1975). Therefore, any adverse effects of acid precipitation on seed or seedling are important.

5.2. Tree growth

The regional studies were based on tree-ring analyses, i.e. studies of past diameter growth by means of increment cores from sample trees (*Abrahamsen et al.* 1975, *Tveite* 1975, *Vestjordet* 1975, *Tveite & Skrøppa* 1976). Tree-ring analyses have otherwise been extensively used in studies of air pollution effects around local emission sources (e.g. *Pollanschütz* 1971).

Dahl & Skre (1971) anticipated that substantial growth reductions due to increased leaching of plant nutrients, especially calcium, by acid precipitation, might already exist in southern regions of Norway. A Swedish study, based on tree-ring analyses of past diameter growth, also indicated poorer growth development during the last decades in regions supposed to be susceptible to acidification (*Jonsson & Sundberg* 1972).

Our main approach has been very similar to the Swedish study by *Jonsson & Sundberg* (1972). Tree-ring development has been compared 1) between regions presumed or known to have different inputs of acid precipitation and 2) between sites getting about the same acid input, but supposed to differ in sensitivity, owing to soil properties.

Increment cores were obtained from the National Forest Survey, which annually collects information about the Norwegian forests according to a systematic clustered sampling scheme. Sample plot information was used to stratify the material into site or regional groups (*Landsskogtakseringen* 1971). The period 1911 – 1972 has been investigated using the data from the survey years 1973 and 1974.

Tree-ring series from about 3,000 plots in the regions Sørlandet and Østlandet were utilized, the main part coming from Sørlandet (Fig. 1). Pine and spruce were studied separately. Plot series within the same region or site group were combined to form average tree-ring series. In the statistical model used, the factors influencing diameter growth are supposed to act multiplicatively. Additive models are obtained by using logarithmic ring widths in the tree-ring series.

Comparisons of regions or site groups were based on difference series which show the relative tree-ring development of two regions or site groups which are to be compared. The difference series were studied by time series analyses (*Skrøppa & Mohn* 1975). Hypothetic linear trend changes in the difference series were tested using the years 1950 and 1960, respectively, as breaking points. The year 1950 was used by *Jonsson & Sundberg* (1972) as the initiation date of possible acidification effects due to increased SO_2 emissions (cf. also *Dovland et al.* 1976). The year 1960 was used as another initiation date to account for possible time delay in growth reactions.

Regional comparisons were made between Sørlandet and Østlandet (Fig. 1), for pine and spruce separately within three height zones (< 300 m, 300 – 600 m, > 600 m alt.). Sørlandet has the higher input of acid precipitation (*Dovland et al.* 1976) and has also been assumed to be more sensitive to acidification than Østlandet due to its shallow soils combined with mostly granitic rocks. The Østlandet region is

also, however, highly influenced by acid precipitation and is not an ideal control area. Also, the lower parts of Østlandet probably receive substantially greater amounts of acid dry deposition than Sørlandet due to local emission sources. The comparisons between Sørlandet and Østlandet are, therefore, of limited value in evaluating effects of different acid input on growth.

No consistent regional growth differences between Sørlandet and Østlandet were found. Somewhat better development of pine stands at lower elevations within Sørlandet was indicated for the period after 1950.

Within Sørlandet, site group comparisons were made between shallow and deep soils, between poor and rich vegetation types, between dry sites and sites influenced by subsurface or surface water flow, and finally between low and high production sites as estimated by the site index method in forest terminology. Pine and spruce were studied separately within the same three height zones as those used in the regional comparisons.

The site group comparisons within Sørlandet yielded no consistent results. Some significant trend changes are indicated, mainly in the spruce comparisons. The trend changes do not, however, support the hypotheses that trees on 1) less productive sites, 2) poor vegetation types, 3) shallow soils or 4) sites uninfluenced by water flow should be more sensitive to soil acidification. An example is given in Figure 13 where spruce stands on shallow soils at medium elevations show somewhat better development in recent years compared with spruce stands on deep soils.

Among possible causes for the indicated trend changes, are changes in cutting practises during recent decades, causing increased stand density. The decrease in diameter growth due to increased stand density may be more marked on better sites with higher initial densities than on poorer sites. Differences between groups in earlier stand history may also be influential. It is difficult to separate and study the possible effects of these factors. A further complication lies in comparisons between site groups which are extreme in

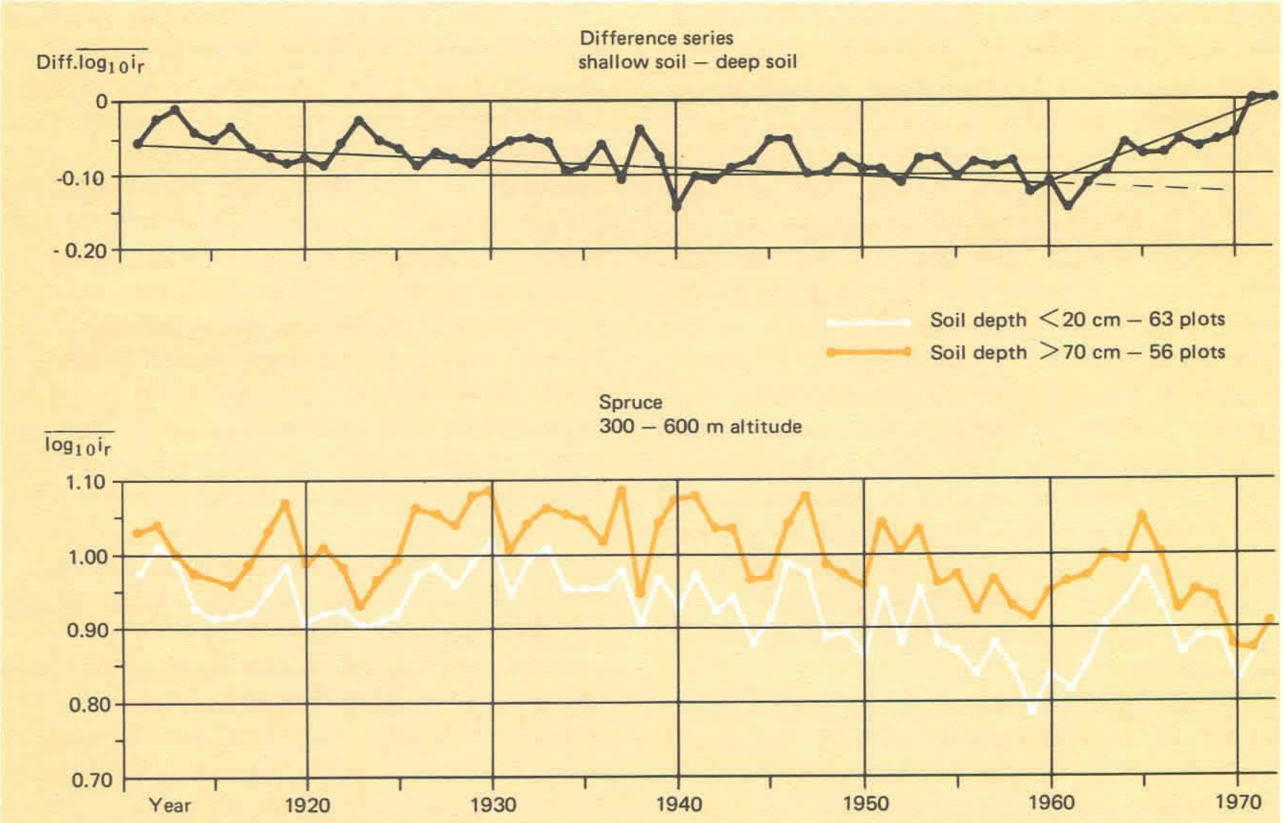


Fig. 13. Tree-ring development of spruce on different soil depth groups and a difference series between the groups. Stands from Sørlandet between 300 and 600 m altitude. The calculated trend and significant trend changes using 1960 as breaking point are shown in the difference series.

$\overline{\log_{10} i_r}$ = average logarithmized annual ring widths (1/10 mm)
Diff. $\overline{\log_{10} i_r}$ = difference between average logarithmic ring widths for the two tree-ring series (from *Tveite* & *Skrøppa* 1976).

ecological factors. Interactions between site group and year, i.e. different growth response to the weather conditions in consecutive years, may create trend changes in growth comparisons between such site groups. Finally, the indicated trend changes may be caused by limited sample size within groups.

The statistical sensitivity of the method used depends on the variability of the difference series. In the regional comparisons between Sørlandet and Østlandet relative changes greater than about 20% will be statistically significant ($P = 0.05$), while 10 – 30% relative changes are needed in site group comparisons within Sørlandet. The number of years used to establish the difference is of minor importance.

Apart from the statistical sensitivity, the main problem in the approach lies in the interpretation of non-experimental investigations. With these difficulties in mind, one may conclude that no clear effects of acid precipitation on diameter growth have yet been detected by these regional tree-ring analyses.

In another study, *Vestjordet* (1975) analysed tree-ring data from thinning experiments within Sørlandet, mainly in pine stands. The study includes an attempt to explain ring width variations caused by tree aging, autocorrelation in the time series, climate and thinning intensity. No clear evidence of influences attributable to acid precipitation was found, but the low sensitivity of the approaches is pointed out.

Height growth was analysed in the field acidification experiments, including an experiment with Norway spruce transplants in the Sønsterud Forest Nursery (Fig. 1) (*Tveite* & *Teigen* 1976). Treatment differences were studied by analysis of variance or covariance with height growth the year before the start of experimentation as covariable. Descriptions of the field experiments on forest soil are given in Chapter 2. The forest nursery experiment has a split-plot design in three blocks where different fertilizer regimes are combined with application of acid "rain".

Within the experimental period (one to three years) no negative effects of acid application were detected. The experiment with lodgepole pine shows a certain stimulation of height growth after the application of 50 mm water per month at pH 4 and pH 3. The difference in height growth between control water and acid treatments amounts to about 26 cm (20%) after the experimental period of three years. The nursery experiment with spruce transplants also shows a stimulation of height growth at pH 4 and pH 3 amounting to about 5 cm (15%) after the three-year experimental period. Only 25 mm of water was applied on each occasion in this experiment, but the watering was more frequent than in the other experiments. An overall picture of the results from the experiments (excluding the forest nursery) is given in Figure 14. No effect on height growth of watering with control water (pH 5.6 – 6.0) is yet apparent in comparison with non-watered plots included in the experiments with lodgepole pine and Scots pine.

Diameter growth in 1975 (the second year of experimentation) was analysed in the Norway spruce experiment on podzol. No effect of acid application is apparent.

Benzian (1965) found optimum height growth of seedlings of Norway spruce, Scots pine and lodgepole pine at soil $pH_{(CaCl_2)}$ of about 4.5 which corresponds to a $pH_{(H_2O)}$ value of about 5.0 (cf. also *Low* & *Brown* 1974). However, *Tamm et al.* (1975) and the SNSF-studies did not demonstrate declining growth of these conifers in acidified podzol soils. *Wood* & *Bormann* (1975b) showed increased productivity of *Pinus strobus* seedlings by increasing acidity in short-time laboratory experiments with simulated acid rain of pH 5.0 – 2.3. Nitrate added to the simulated rain as nitric acid might have caused the growth increases. In a similar study *Wood* & *Bormann* (1974) found no effect on the growth of *Betula alleghaniensis* Britt. seedlings when exposed to mists of pH 3.0 and above. Significant growth decreases were encountered at pH 2.3, foliar tissue damage most probably being the cause. Nitric acid was not applied in the latter study. *Cogbill* (1975) did not succeed in correlating acid precipitation to forest growth by tree-ring analyses in eastern North America, claiming the reason to be the unknown initiation date of acid precipitation and the large variance of tree growth estimates.

Short-term growth results from acidification experiments must be treated with caution. They indicate, however, that tree growth may be reasonably stable when the tree-soil system is stressed by acid water. Regional tree-ring investigations of possible acidification effects are very difficult to interpret due to problems of method and lack of sensitivity in the approaches. The failure to detect effects in the regional investigations may, however, to some extent be sup-

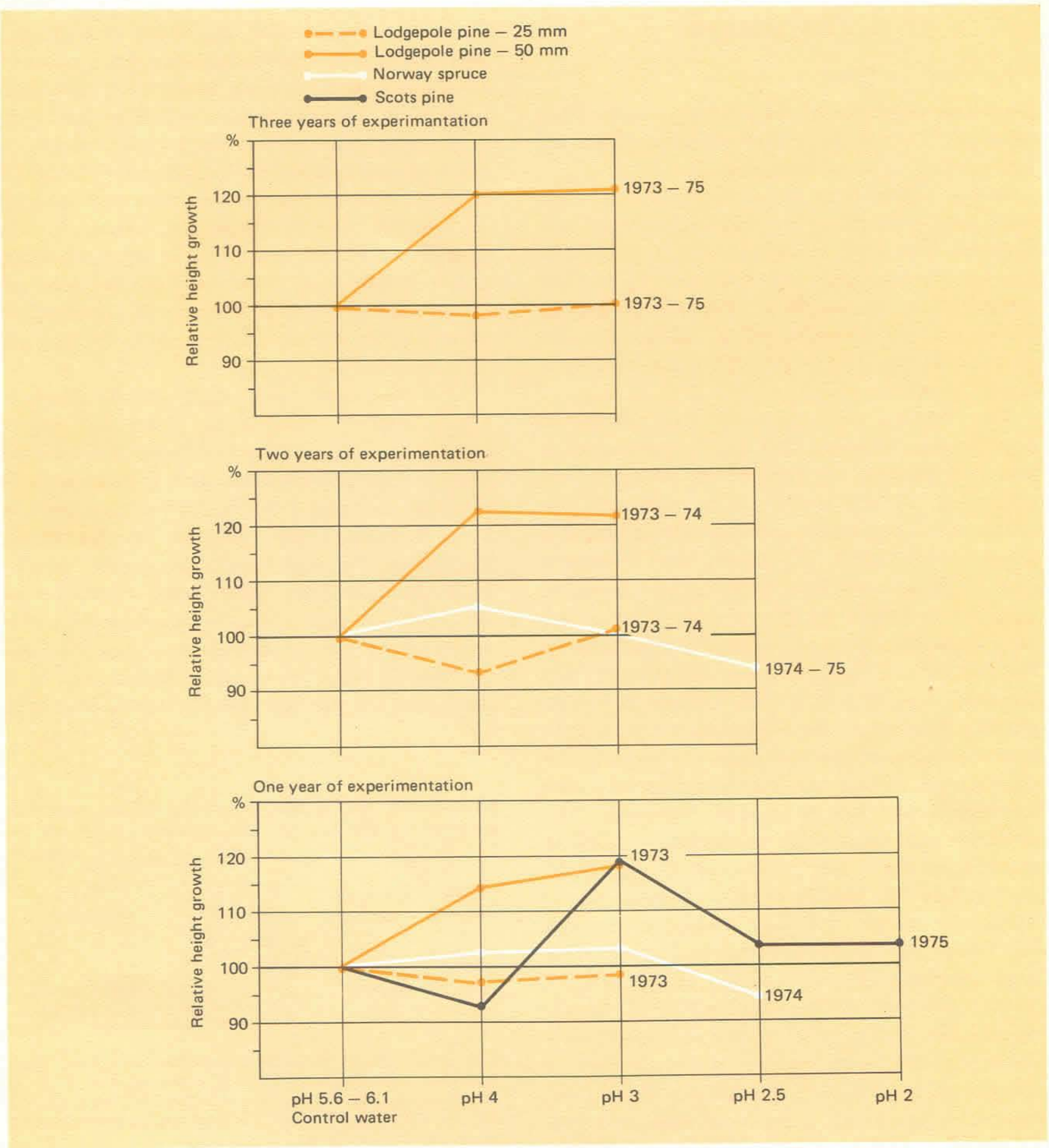


Fig. 14. Height growth at different acidity levels related to height growth on plots receiving control water. Data from field experiments in forest soil and for different periods of experimentation. The actual years of experimentation are indicated (from *Tveite* & *Teigen* 1976).

ported by the experimental growth results. The acid precipitation also contains substantial amounts of ammonium and nitrate (*Dovland et al.* 1976). The possible beneficial effects on growth of this nitrogen supply may be most pronounced on sites which are also assumed to be the most sensitive to acidification. If so, the nitrogen supply may be an additional factor in the explanation of the results of the growth comparisons between site groups in the regional investigations.

6. Discussion

6.1. Effects on forest

The main objective of the studies described has been to examine direct and potential effects of acid precipitation on tree growth.

It was found that the establishment of Norway spruce seedlings in acidified mineral soil dropped from 80% at soil pH of 4.8, to 20% at pH 3.8. Germination was influenced less. The precipitation in southern Norway is seldom below pH 4.0 (*Dovland et al.* 1975), but the throughfall can be considerably more acid (Tab. 3, and *Haugbotn* 1976).

The regional tree-ring study has not shown any growth influence that can be attributed to acid precipitation. In view of the relatively low sensitivity of this investigation, and with the results from the field experiments in mind, this result is reasonable. Treatment with simulated rain of pH 4 in the field experiments caused no decrease in height growth of conifer trees and only small effects on soil chemical properties. In fact, in the lodgepole pine experiment this treatment resulted in a 20% increase in height growth. This might be explained by the higher concentrations of specific plant nutrients in the soil solution which are manifested in increased leaching from the lysimeters. However, the elements most susceptible to leaching – calcium and magnesium – are usually not growth limiting factors in boreal conifer forests. These forests are mainly deficient in mineral nitrogen (e.g.*Tamm* 1975) which is deposited in relatively large amounts (*Dovland et al.* 1976). Results from watershed studies (*Gjessing et al.* 1976), throughfall studies and lysimeter experiments show that the forest absorbs the major part of the deposited nitrogen. At present, these facts do not support the hypothesis that acid precipitation is likely to reduce forest production. In Germany where the atmospheric nitrogen deposition is much larger than in Norway, short-term increases in productivity have even been suggested (*Ulrich* 1975).

However, the potential long-term effect of increased leaching of plant nutrients which are today abundant, should not be ignored. In order to evaluate this effect the leaching has been related both to the deposition of nutrients with precipitation and to the pool of exchangeable nutrients in the soil. The pool of exchangeable nutrients is, however, continuously supplemented by weathering. The weathering, which is likely to increase with the input of hydrogen ions (*Loughnan* 1969), may therefore counteract the increased leaching. However, it should be pointed out that the reduction in base saturation in the upper parts of the mineral soil (A-layer) in the podzol experiments indicates that weathering has not kept up with the increased leaching of divalent ions in particular. Therefore, the importance of the weathering in this connection is not known and weathering studies must be carried out in order to evaluate the total effect of acid precipitation on the supply of available plant nutrients in the soil.

The losses of plant nutrients by leaching might also be related to losses by timber harvesting (Tab. 7). The lysimeters that received only natural precipitation with a prevailing pH of about 4.5 have a net loss by leaching which is 2 to 5 times larger than the loss by timber harvesting. The net losses are slightly smaller from the lysimeters additionally supplied with non-acidified water, whereas those supplied with water of pH 3 have losses up to 12 times as large as those caused by timber harvesting. It is demonstrated that the relative losses of magnesium are much larger than that of calcium and potassium.

Table 7. The ratio between annual net nutrient losses from lysimeters and estimated annual losses by timber harvesting.

Nutrient element	Non-watered lysimeters	Watered lysimeters			
		pH 5.6 – 6		pH 3	
		mm/month		mm/month	
		25	50	25	50
Ca	2.8	1.9	2.3	4.6	5.2
Mg	4.9	2.5	3.8	6.5	11.6
K	1.8	0	2.8	– 0.6	4.9

The annual timber production (including bark) of Norway spruce on the soils studied has been estimated at 5 m^3/ha. A corresponding timber harvest removes about 270 mg Ca, 40 mg Mg and 120 mg K per m^2 per year calculated from various studies, e.g. *Tamm* (1970).

It must be emphasized that the results from the field experiments are highly preliminary. Tenable results of studies in forest ecosystems cannot be obtained after only a period of 2 – 3 years. On the background of the results obtained it is difficult to forecast the long-term impact of acid precipitation. However, the significant increase in leaching of plant nutrients from soil and foliage with increasing acidity of the simulated rain, and the decrease in soil pH and base saturation observed in the field plots, imply that

acid precipitation must be considered a potential threat to forest and other natural terrestrial ecosystems.

6.2. Effects of vegetation and soil on water quality

Since bodies of fresh water occupy about 5% of the area of Norway, only a small proportion of the precipitation is falling directly into watercourses. Most of it percolates through terrestrial ecosystems before entering the groundwater and, subsequently, the watercourses. In this way interactions between precipitation and vegetation and soil will modify the water quality.

Interaction between vegetation and rainwater implies that water quality is altered upon passing through the vegetation. Our results show that the acidity of throughfall water below spruce and pine was different from that below birch and specific species of the ground flora. Adsorption of hydrogen ions in the forest canopy has been observed both in deciduous and in conifer forests (*Eaton et al.* 1973, *Cole & Johnson* 1974).

As also demonstrated in our studies, vegetation transpires and intercepts substantial amounts of water, thus efficiently retarding leaching. This effect has been clearly demonstrated by *Likens et al.* (1970).

Despite the transpiration from vegetation and evaporation from the soil surface a substantial part of the soil water is lost in run-off. The chemical properties of the leachate are strongly influenced by the amount of exchangeable metal cations in the soil. In rich soils with pH above about 5, hydrogen ions from precipitation mainly exchange nutrient ions. In more acid soils, and especially if pH of the soil solution is below 4.5, hydrated aluminium ions will also be exchanged and leached from the soil (e.g.*Black* 1968). Acid leachate containing aluminium ions has a high buffer capacity against decrease in acidity. Therefore, such water has a detrimental effect on the water quality of rivers and lakes.

Water quality also depends on soil depth. Soil acidity generally decreases with increasing soil depth. The pH in the raw-humus in one of the field experiments is about 4.0, 30 cm farther down it is 5.2 and in the ground water level 2 – 3 m below the surface it is about 6. This pH gradient means that the pH of the percolation water increases with increasing soil depth, and that aluminium and other ions exchanged in the upper soil layers will precipitate out lower in the soil. In general, therefore, the quality of ground water in deep soil is less influenced by rain and snow chemistry than the ground water in shallow soils. This fact should be viewed relative to the soil depth distribution in Norway. Almost 50% of the total land area is above the timber line, consisting largely of bare rocks and shallow soil layers. In eleven counties of southern Norway studied by *Låg* (1967), about 13% of the land area below the timber line has shallow soils and bare rocks and about 60% is productive forest areas. About 55% of the productive forest is on soil deeper than 70 cm, 35% on soils from 20 to 70 cm deep and 10% is on shallower soils.

Forests are generally assumed to improve water quality. As mentioned above, this is partly due to their specific vegetation, but mostly because of the deep soils associated with forests.

7. Summary

This report summarizes the preliminary results of studies in conifer forests obtained in the first phase (1972 – 75) of The SNSF-project. The results are mainly based on sampling of the natural precipitation above and beneath vegetation canopies, on the application of simulated acid rain to field plots and lysimeters, and on regional tree growth surveys.

Compared to incident rain, the throughfall under tree crowns was enriched in sulphate, chloride, sodium, potassium, calcium and magnesium. This is partly due to wash-off of dry deposits and partly to foliar leaching. Birch, in contrast to pine and spruce, reduced the acidity of the rain. Increasing rain acidity apparently caused increased foliar leaching of calcium, magnesium and other cations. This result was confirmed in a field plot experiment with Norway spruce.

Increasing acidity (pH 6 to 2) of the simulated acid rain in the field plot experiments reduced the pH, the content of exchangeable metal cations and the base saturation in the top layers of podzol soils. An intermediate soil

between podzol and brown earth was influenced less by acid "rain".

Lysimeter experiments with a podzol soil revealed that the pH of the leachate was significantly decreased by the acid "rain". In the podzol-brown earth lysimeters, the pH of the leachate was not influenced.

Net loss of nutrient elements was, with the exception of calcium, much smaller from the podzol-brown earth than from the podzol soil. Differences in nutrient budgets between the two soil types may be related to differences in inputs of hydrogen ions, contents of exchangeable ions in the soils and ground cover vegetation.

The experiments did not demonstrate consistent effects of acid treatments on decomposition processes or on the abundance of enchytraeids (*Oligochaeta*) in the soil. The rate of nitrification and nitrogen fixation was very low in the soil of the field experiments, and effects of the acid "rain" were not observed.

Simulated rain with pH 2 and 2.5 produced necrosis on trees and herbs. The moss vegetation was significantly reduced by applications of water at pH 3 or lower.

Experiments with Norway spruce on artificially acidified mineral soil indicate that germination and seedling establishment have a broad optimum within a soil pH range from 4.4 to 5.4. Within this range about 80% of the seedlings were able to become established, whereas only 20% became established at soil pH 3.8.

Regions differing to some extent in exposure to acid deposition have been compared with regard to past diameter growth. So far no effects have been found that can be related to acid precipitation. Nor have effects been detected on sites supposed to be most sensitive to acidification.

The studies on height growth in the field experiments did not reveal any negative effect of acidification on Norway spruce, Scots pine or lodgepole pine. An increase in height growth at pH 4 and 3 was observed in the lodgepole pine experiment and in an experiment with Norway spruce in a forest nursery.

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